

*EFFECTS OF STEP SIZE AND BREAK-POINT
CRITERION ON PROGRESSIVE-RATIO PERFORMANCE*

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Key pecking by pigeons was maintained by arithmetic progressive-ratio schedules of food delivery. Successive conditions arranged different step sizes, and each condition remained in effect until behavior appeared stable. Each session continued until a period of time passed in which no key pecks were recorded (the break-point criterion); both a 5-min and a 15-min criterion were tested across a range of step sizes. Average breaking points (i.e., the largest ratio completed) were relatively unaffected by step-size magnitude, whereas the average number of ratios completed and average response rates generally declined across increasing step sizes. Within sessions, preratio pauses were relatively short and fairly constant in duration as the ratio increased; pause durations increased rapidly near the end of a session. The relation between the average number of completed ratios and step size was described well by a power function [$y = b(x^a)$, in which y represents the average number of completed ratios, x represents the step size, and a and b are fitted parameters]. Increasing the break-point criterion from 5 to 15 min resulted in increased values of b , whereas parameter a was relatively unaffected and was close to -1 (consistent with the lack of effect of step size on breaking point). This function also provided an excellent description of data drawn from previous reports.

Key words: progressive ratio, reinforcer efficacy, step size, break-point criterion, key peck, pigeons

Schedules of reinforcement are among the most powerful tools in experimental psychology. As Zeiler (1984) and others (e.g., Keller & Morse, 1968; Sidman, 1960) have noted, schedules both establish and maintain lawful patterns of behavior and also may determine to a large extent how other variables will influence behavior. Although schedules are of paramount importance in the design of an extraordinary variety of experimental techniques, the relations between basic schedule parameters and the behavior they maintain are often of subsidiary interest. A good example of an increasingly used, but rarely examined, tool is the progressive-ratio (PR) schedule of reinforcement. In the original description of PR schedules (Findley, 1958), a number of responses (the ratio) was required for a reinforcer presentation, and that number increased from one reinforcer delivery to the next. A parameter termed the *step size* determined how rapidly the response requirements increased. For example, a step

size of 100 (i.e., PR 100) would deliver the initial reinforcer after 100 responses, the second after 200 responses, and so on. The defining features of this schedule, then, are that (a) a number of responses is required for reinforcer delivery and (b) this number increases across reinforcer deliveries.

Hodos (1961) introduced a variant of Findley's procedure that treated the PR schedule as a technique to measure *reward strength*. In his procedure, PR schedules were studied in isolation (Findley's experiments had embedded PR schedules in a concurrent-schedule context), and a session continued until a period of time (15 min) passed in which the subject (a rat) failed to make the designated response (a lever press). The last ratio completed by the subject before the session ended was termed the *breaking point*, and the period of time without a response that was required to terminate a session was called the *break-point criterion*. Hodos argued that this general procedure could measure reward strength (or, in other terms, reinforcer efficacy), guessing that "better" rewards would lead to higher breaking points. In his experiment, rats' breaking points did increase as a function of concentration of sweetened condensed milk, a relation that has been replicated and extended in subsequent reports (e.g., Baron, Mikorski, & Schlund, 1992; Cheeta, Brooks, & Willner, 1995; Hodos &

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Kalman, 1963; Skjoldager, Pierre, & Mittleman, 1993). In fact, this general line of reasoning, that performance on PR schedules can be treated as an index of reinforcer efficacy, has since stimulated a tremendous amount of research, especially in the area of drug self-administration (e.g., Griffiths, Findley, Brady, Dolan-Gutcher, & Robinson, 1975; Hoffmeister, 1979; Risner & Silcox, 1981; Roberts, Loh, & Vickers, 1989; Spear & Katz, 1991; Winger & Woods, 1985; Woolverton, 1995; Yanagita, 1973).

Although PR schedules made their first appearance almost 40 years ago and their popularity among researchers has grown phenomenally (especially in the past 10 to 15 years), very few experiments have reported the effects of manipulating fundamental schedule variables. In a review of the rapidly expanding drug self-administration literature, Katz (1990) noted that "there are few parametric studies available on progressive-ratio schedules with food as a reinforcer; these studies would prove valuable as guides for the more difficult studies using drugs as reinforcers" (p. 298). One parameter that might influence performance maintained by PR schedules is the size of each ratio increment. Hodos and Kalman (1963) reported that as step size increased (range, 2 to 40 in an arithmetic PR), so did breaking points of rats for which pressing a lever was maintained by liquid reinforcers. Their conclusions, however, were based upon only six sessions of exposure to each step size, which is significantly less experience than most investigators report as necessary to establish stable patterns of responding on many schedules of reinforcement (e.g., Cumming & Schoenfeld, 1960); furthermore, no conditions were directly replicated. Uzunoz (1979) found that step size (range, 1.10 to 1.12) in a geometrically increasing progression had no systematic effect on breaking points when presses by rats on one of two available levers produced food (i.e., only one lever was active, but no distinctive stimuli were associated with which one it was); when only one lever was available, however, breaking points generally increased with step sizes (range, 1.05 to 1.09). Although Hodos and Kalman's (1963) and Uzunoz's (1979) results both suggest that breaking points can increase with larger step sizes, neither study has been replicated in a systematic

fashion (nor have the similarities and differences between performances maintained by arithmetic and geometric progressions been determined).

Another factor that might influence performance maintained by PR schedules of reinforcement is the break-point criterion. This parameter is generally intended to indicate when responding is weakly maintained by the scheduled consequence, but different reports have employed widely divergent criteria. For example, Hodos' (1961) break-point criterion was 15 min without a response, but another report shortened the criterion to 3 min (Dantzer, 1976). Others have employed a break-point criterion that specifies a temporal limit for completing each ratio, and the duration of this period has ranged from 8 min (Macenski, Schaal, Cleary, & Thompson, 1994) to 60 min (Thompson, 1972). Some procedures set a time limit on overall session duration (e.g., Jones, LeSage, Sundby, & Poling, 1995); several reports from the same laboratory (Buffalo, Gillam, Allen, & Paule, 1993; Ferguson & Paule, 1993; Paule et al., 1992) have embedded PR schedules in a multiple schedule (cf. Ferster & Skinner, 1957) context in which PR components were limited to 10 min. As far as we know, however, no published experiment has directly compared the effects of manipulating the type or length of break-point criteria on PR performance.

The present experiment was designed to provide a detailed description of the effects of step size and break-point criterion on breaking points reached by pigeons on an arithmetically increasing PR schedule of food delivery. The general procedure consisted of holding the break-point criterion constant at either 5 or 15 min while varying the step size in an ascending series across conditions. Each step-size condition was continued until breaking points were judged to be stable. In addition to breaking points, data were collected on within-session response patterning, total responses per session, response rate, and the number of ratios completed per session. The average number of completed ratios per session was found to vary in an orderly fashion with changes in step size and break-point criterion. A power function described these relations well and also provided an excellent description of data drawn from previous reports.

METHOD

Subjects

Seven adult White Carneau pigeons (*Columba livia*) of indeterminate sex, obtained from Palmetto Pigeon Plant, served as subjects. Each bird had prior experience with experimental procedures; 4 of the 7 (Subjects 2243, 3858, 3883, and 3888) had previously pecked response keys in an experiment investigating effects of cocaine on a multiple PR fixed-ratio (FR) baseline, whereas the remaining 3 (Subjects 5615, 5642, and 5775) had been exposed to a variety of operant contingencies in an undergraduate laboratory course. The pigeons were housed individually in a colony room (16:8 hr light/dark cycle) with free access to water and grit. They were maintained at 80% of free-feeding body weights (determined over a 10-day period prior to the experiment) via postsession supplemental feedings, when necessary.

Apparatus

An operant conditioning chamber for pigeons, measuring 31 cm long by 35 cm deep by 35 cm high, was used. Three translucent response keys were mounted horizontally, 25 cm above the floor, behind 2.5-cm holes cut through the front wall. The keys were 8.5 cm apart, center to center, and could be transilluminated with colored lights. Only the center key was used in this experiment. A minimum static force of 0.15 N on the response key was required to register a response. A 1.1-WDC lamp (housetlight), which provided low-level illumination, was located above the center key and 3 cm below the ceiling. Centered 13 cm below the row of response keys was a rectangular opening through which the pigeon could gain access to mixed grain when a hopper was raised. Extraneous sounds were masked by white noise (95 dB), provided by a wall-mounted speaker in the room housing the conditioning chamber, and by a ventilating fan. An IBM-compatible computer located in an adjacent room arranged experimental events and collected data via the ECRBasic control system (Walter & Palya, 1984), and a Gerbrands cumulative recorder produced real-time records of responding.

Procedure

One session was conducted per day, per subject, 7 days per week. Each session was

preceded by a 5-min blackout in which pecks were not recorded and food was not available. Availability of mixed grain was correlated with the onset of the houselight and the transillumination of the center key with red light. Reinforcement consisted of 5-s access to mixed grain, during which time the feeder opening was illuminated and the keylight and houselight were darkened. Pecking the center key was maintained by an arithmetic PR schedule of food delivery, with the increment size varying across conditions. All subjects were tested first with the 5-min break-point criterion (i.e., a session ended when 5 min elapsed without a peck). Step sizes were increased from one condition to the next, until a step size that maintained very little responding was reached (i.e., until relatively few ratios were completed in each session and average response rates were low). Following this, a second ascending series of different step-size conditions was studied, after which the smallest step-size condition was replicated. Then, the break-point criterion was increased to 15 min and a single sequence of increasing step-size conditions was examined (Subjects 5642 and 5775 did not participate in this portion of the experiment due to time constraints in the laboratory). Following this, a final condition arranged a PR 5 schedule for 4 of 5 subjects. Table 1 shows the sequence of conditions and the number of sessions conducted during each condition for every subject.

Three stability criteria were used to determine condition changes. First, each condition continued for at least 25 sessions (this number was chosen based upon previous work in this laboratory). Second, a condition was not changed unless behavior appeared stable in plots of daily breaking points and patterns of responding on cumulative records of responding (i.e., no upward or downward trends were apparent in the break-point data and cumulative records appeared to be similar to those typically observed for responding maintained by ratio schedules). Third, a condition continued until no breaking point observed during the final 10 sessions of a condition fell outside the previously observed range for that condition (i.e., if a condition remained in effect for 25 sessions, each breaking point observed during Sessions 16 through 25 was required to fall within the

Table 1
Step sizes (and number of sessions in each condition).

Condi- tion	Pigeon						
	2243	3858	3883	3888	5615	5642	5775
5-min break-point criterion							
1	5 (32)	5 (64)	5 (33)	5 (33)	5 (29)	5 (34)	5 (41)
2	10 (39)	10 (29)	10 (61)	10 (61)	10 (39)	10 (53)	10 (47)
3	20 (42)	20 (32)	20 (55)	20 (25)	20 (28)	20 (30)	20 (64)
4	40 (64)	3 (25)	40 (50)	1 (42)	40 (28)	40 (94)	40 (42)
5	80 (48)	8 (37)	80 (35)	3 (33)	80 (28)	80 (50)	80 (38)
6	3 (47)	15 (40)	160 (27)	8 (35)	3 (64)	160 (32)	
7	8 (76)	40 (45)	3 (31)	3 (54)	8 (26)	320 (32)	
8	15 (47)	80 (27)	8 (39)		15 (94)	3 (53)	
9	30 (46)	3 (33)	15 (50)		30 (39)	8 (38)	
10	60 (32)		40 (35)		60 (39)	15 (43)	
11	3 (29)		120 (32)		3 (29)	30 (27)	
12			3 (67)			60 (26)	
13						120 (34)	
14						240 (30)	
15						5 (28)	
15-min break-point criterion							
1	3 (15 ^a)	3 (65)	3 (9 ^a)	3 (51)	3 (30)		
2	8 (45)	8 (46)	8 (29)	8 (40)	8 (39)		
3	15 (33)	15 (47)	15 (26)	15 (40)	15 (35)		
4	30 (26)	30 (28)	30 (27)	30 (80)	30 (26)		
5	60 (42)	60 (32)	60 (39)	60 (47)	60 (39)		
6	120 (27)	5 (26)	120 (41)	120 (43)	5 (29)		
7	5 (55)		240 (27)	5 (37)			

^a Condition was terminated before key pecking met the stability criteria because session durations regularly exceeded 3 hr and interfered with laboratory protocol. Hence, data from these conditions are not included in the present analysis.

range observed during Sessions 1 through 15 of that condition).

RESULTS

Breaking Points

All figures presented in this and every other section show data taken from the final 10 sessions in each condition (i.e., the stable block of sessions). Figures 1 and 2 show average breaking points as a function of step size for each pigeon for the 5-min and the 15-min break-point criteria, respectively. Note that the horizontal axes are scaled logarithmically and identically across subjects; the vertical axes are scaled linearly, but the absolute ranges are different for each subject. Figure 1 shows that average breaking points generally remained fairly constant (Subjects 3858, 3883, 3888, and 5775) or increased (Subjects 2243, 5615, and 5642) across a range of step sizes when the break-point criterion was fixed at 5 min during the first ascending sequence of step sizes. Sub-

ject 3858's breaking points, for example, were confined between approximately 42 and 64 responses across step sizes ranging from 3 to 80 responses, with no obvious trend related to step-size magnitude. Subject 5642's breaking points, on the other hand, increased from around 83 responses at a step size of 3 to approximately 384 responses at a step size of 160.

Replications of conditions usually produced similar average breaking points. In two cases (Subject 3858 at a step size of 3 and Subject 3883 at a step size of 40), replications resulted in almost identical average breaking points compared with those observed in the original conditions. For most subjects, the second ascending sequence of step sizes resulted in effects that were quite similar to those of the first sequence. For the subjects whose breaking points had increased across larger step-size values during the first sequence (Subjects 2243, 5615, and 5642), however, the second sequence of increasing step-size conditions produced a relatively flatter

5-min break-point criterion

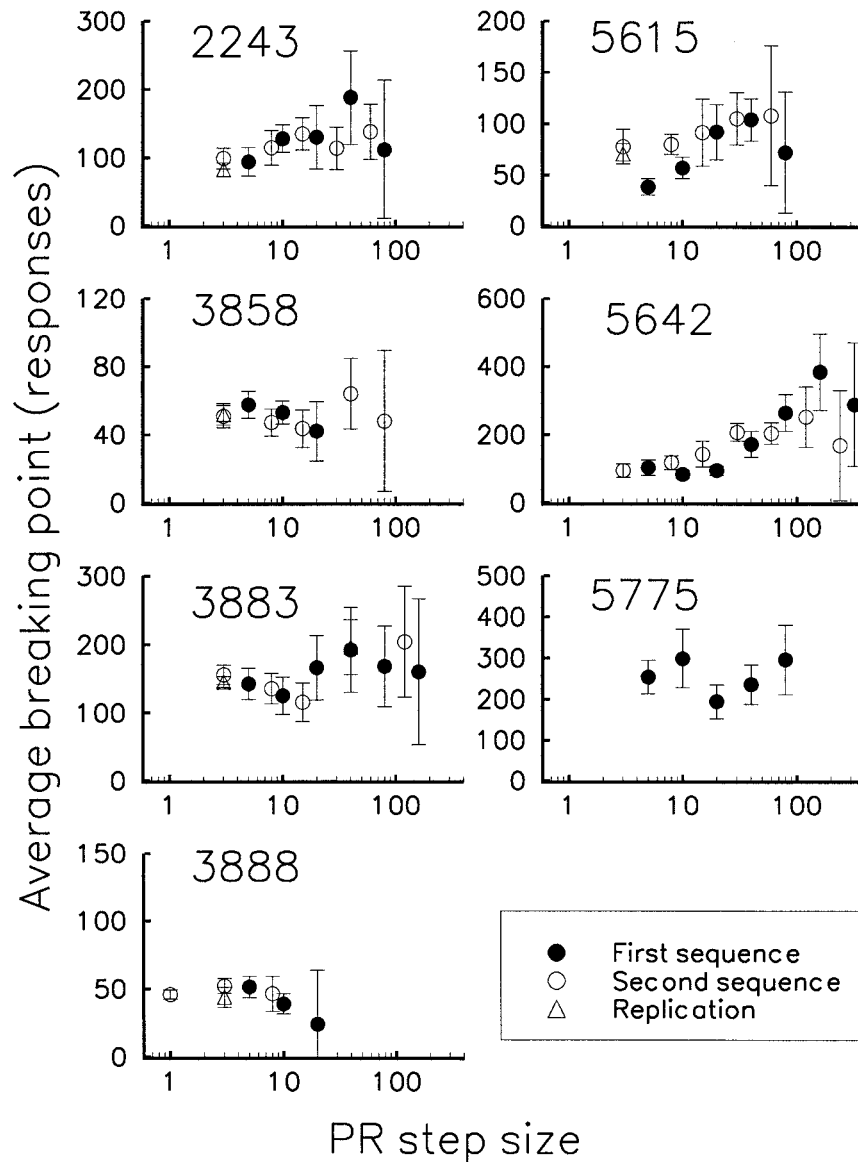


Fig. 1. Mean breaking points across the last 10 sessions as a function of PR step size for each pigeon with the 5-min break-point criterion. Filled points correspond to the first sequence of increasing step sizes, open points refer to the second sequence, and open triangles correspond to direct replications of a specific step size. Vertical bars represent ± 1 SD. Note that the horizontal axis is scaled logarithmically.

break-point function. For Subjects 2243 and 5642, this flattening was a consequence of reduced breaking points at larger step sizes during the second sequence of conditions, whereas for Subject 5615, breaking points at

small step sizes increased relative to those observed during the first sequence. For all subjects, variability around the average breaking points was greatest at the largest step sizes tested. This is somewhat misleading, as others

15-min break-point criterion

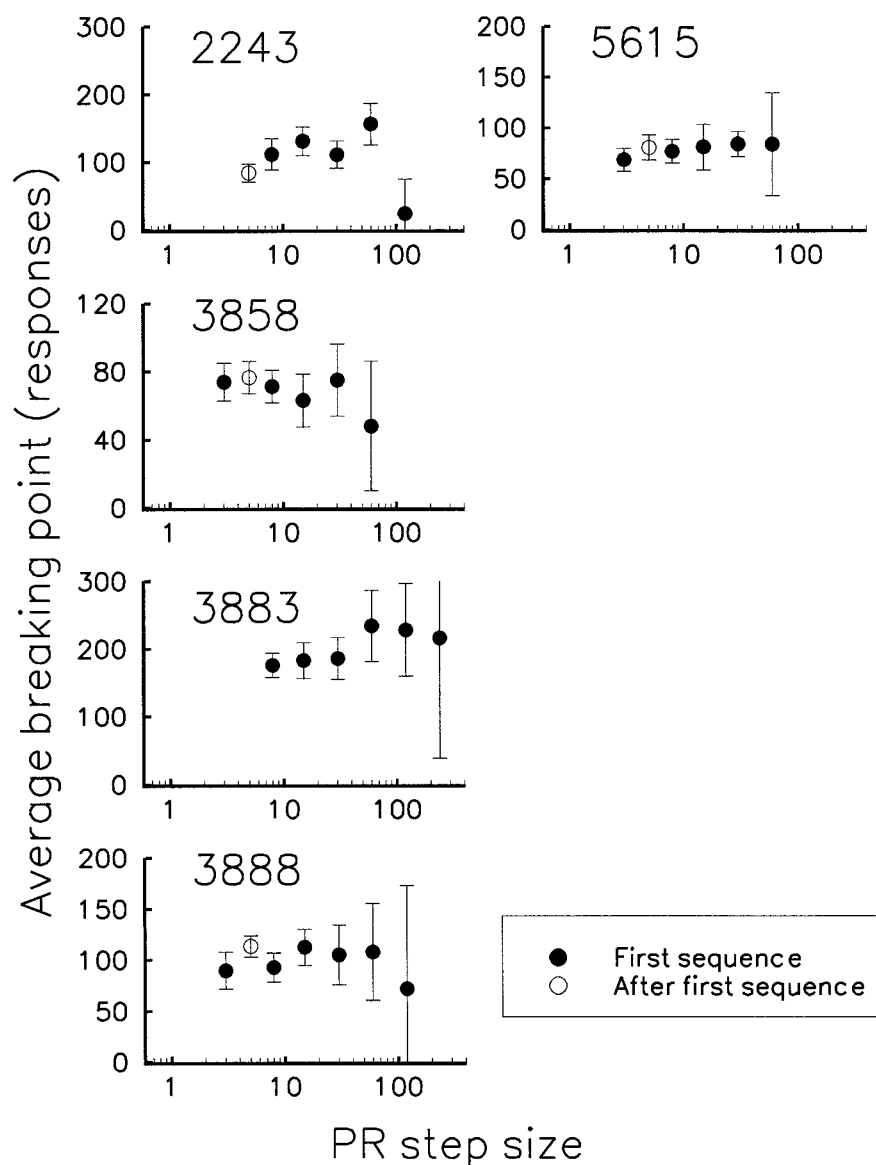


Fig. 2. Mean breaking points as a function of PR step size for each subject with the 15-min break-point criterion. Other details are the same as in Figure 1.

have argued, because the schedule inherently imposes a bias towards increased variability at relatively large step sizes (see Depoortere, Li, Lane, & Emmett-Oglesby, 1993, for an in-depth discussion of this point). Other measures of day-to-day performance that do not

impose this bias, such as the number of ratios completed per session (see below), indicated that, excluding the largest step-size condition, variability in responding did not increase across step-size magnitude.

Figure 2 shows that average breaking

points were relatively constant across step sizes for each subject with the break-point criterion fixed at 15 min. For example, Subject 5615's breaking points ranged from about 68 responses at a step size of 3 to approximately 84 responses at a step size of 30.

When step sizes were increased from one condition to the next, breaking points often increased temporarily as well. With the 5-min break-point criterion, the breaking point observed in the first session of a new, larger step-size condition was greater than the average breaking point from the last 10 sessions in the smaller step-size condition in 90.4% of these condition transitions (individual-subject range, 75% to 100%). With the 15-min criterion, this occurred in 95.5% of the transitions (individual-subject range, 75% to 100%).

Number of Ratios Completed

Figures 3 and 4 show the average number of completed ratios per session as a function of step size in log-log coordinates for each subject with the 5-min and 15-min break-point criteria. Note that the average number of completed ratios for a particular condition is directly proportional to the corresponding breaking point shown in Figures 1 and 2 (i.e., the number of completed ratios in a particular condition can be obtained by dividing the average breaking point by the corresponding step size). Figure 3 shows that, for every subject, the average number of ratios completed decreased across increasing step sizes. Furthermore, the function is strikingly linear in these coordinates for all subjects. The dashed lines represent the best fitting power functions of the form $y = b(x^a)$, in which y represents the average number of ratios completed, x represents the step size, and a and b are free parameters.

Table 2 shows the values of both free parameters a and b for each subject and the proportion of variance accounted for by the best fitting power functions. Best fitting functions were determined on logarithmically transformed data via the conventional least squares method. With the 5-min break-point criterion, the parameter a , which represents the slope of this function in log-log coordinates, was slightly less than or about equal to -1 (a slope of exactly -1 translates into an absolutely flat function relating breaking

point to step size). The parameter b , on the other hand, refers to vertical displacements of the fitted curves in log-log coordinates (i.e., similar to an intercept), with larger b values shifting a function upward. This parameter varied across subjects from 51.41 (Subject 3858) to 245.17 (Subject 5775). Translated into PR performance, a function with a larger b value is correlated with a greater number of ratios completed (and greater breaking points) at all step sizes, compared with a function with a smaller b value (given equivalent values of a). The best fitting power functions accounted for most of the variance in each subject's data, and R^2 values ranged from .91 (Subject 5615) to .99 (Subjects 3858, 3883, and 3888).

Figure 4 and Table 2 indicate that the relation between average number of completed ratios and step size with the 15-min break-point criterion was generally quite similar to that observed with the 5-min criterion. Average number of completed ratios decreased across increasing step sizes, and the decline again is linear in log-log coordinates (Subject 2243's data from the PR 120 condition were not included in the curve-fitting analysis because key pecking in that condition was poorly maintained). Table 2 shows that values of a were again clustered around -1 , whereas b values ranged from 53.79 (Subject 2243) to 150.02 (Subject 3883). Values of a were generally similar across the 5-min and 15-min break-point criteria within individual subjects; on the average, values of a were 4.8% larger with the 15-min criterion (the percentage change was calculated only for those subjects tested with both the 5-min and 15-min break-point criteria, and the changes are presented relative to the values of a obtained with the 5-min criterion). The values of b , however, were larger with the 15-min criterion for 4 of 5 subjects (not Subject 2243); on the average, values of b were 42.9% larger (the percentage change for b was calculated as it was for a). Thus, increasing the break-point criterion from 5 to 15 min appeared to have little effect on the slope of the function relating average number of completed ratios to step size, but the function was generally shifted upward with the longer break-point criterion. As with the 5-min criterion, best fitting power functions accounted for most of the variabil-

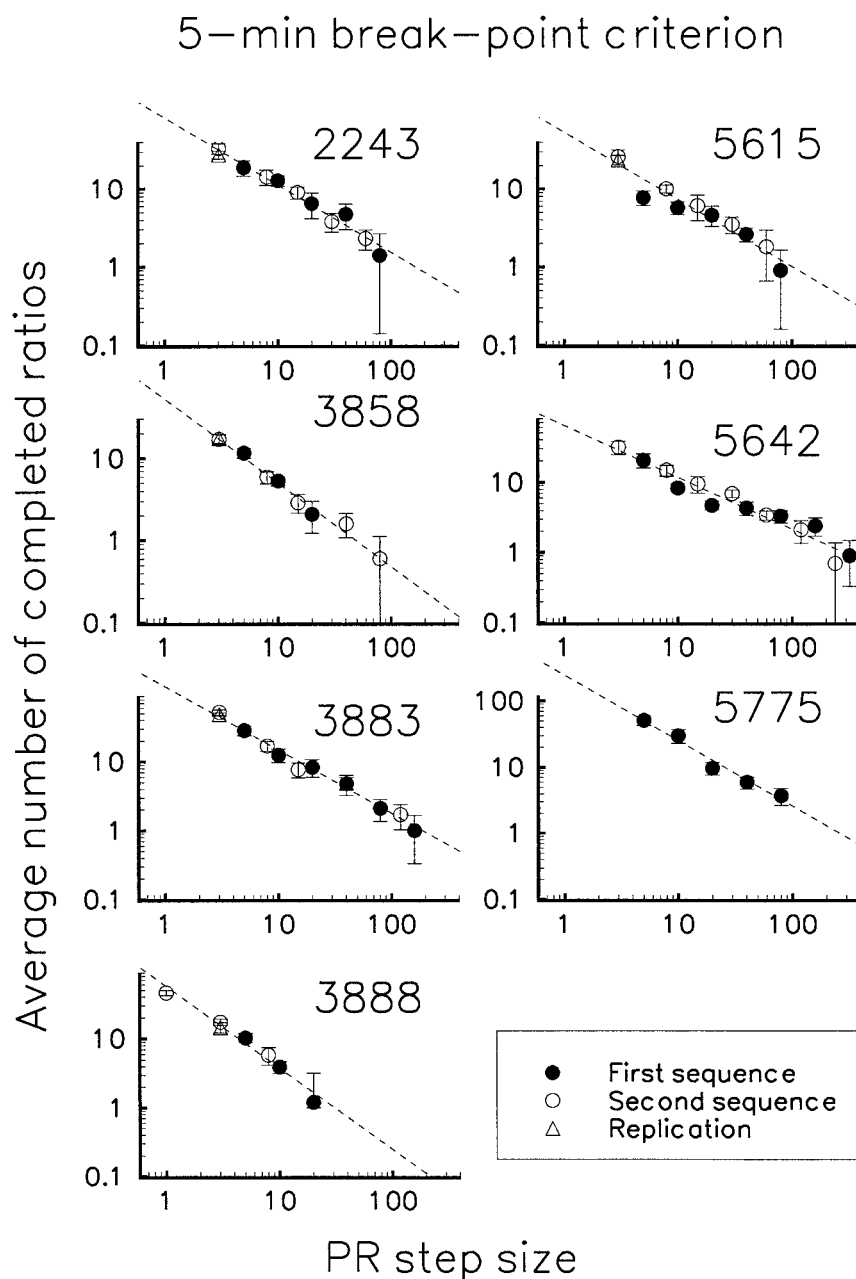


Fig. 3. Average number of completed ratios as a function of PR step size for each subject with the 5-min break-point criterion. Vertical bars represent ± 1 SD, and the dashed lines show the best fitting functions for each subject's data. Note that both axes are scaled logarithmically.

ity in each subject's data (R^2 ranged from .86 to 1.00).

Average Rate of Responding

Figures 5 and 6 show the average rate of responding (pecks per minute) as a function

of step size for each pigeon with the 5-min and 15-min break-point criteria. Note that whereas the horizontal axes are scaled logarithmically and identically, the vertical axes are scaled arithmetically and the ranges are different across pigeons. Figure 5 shows that

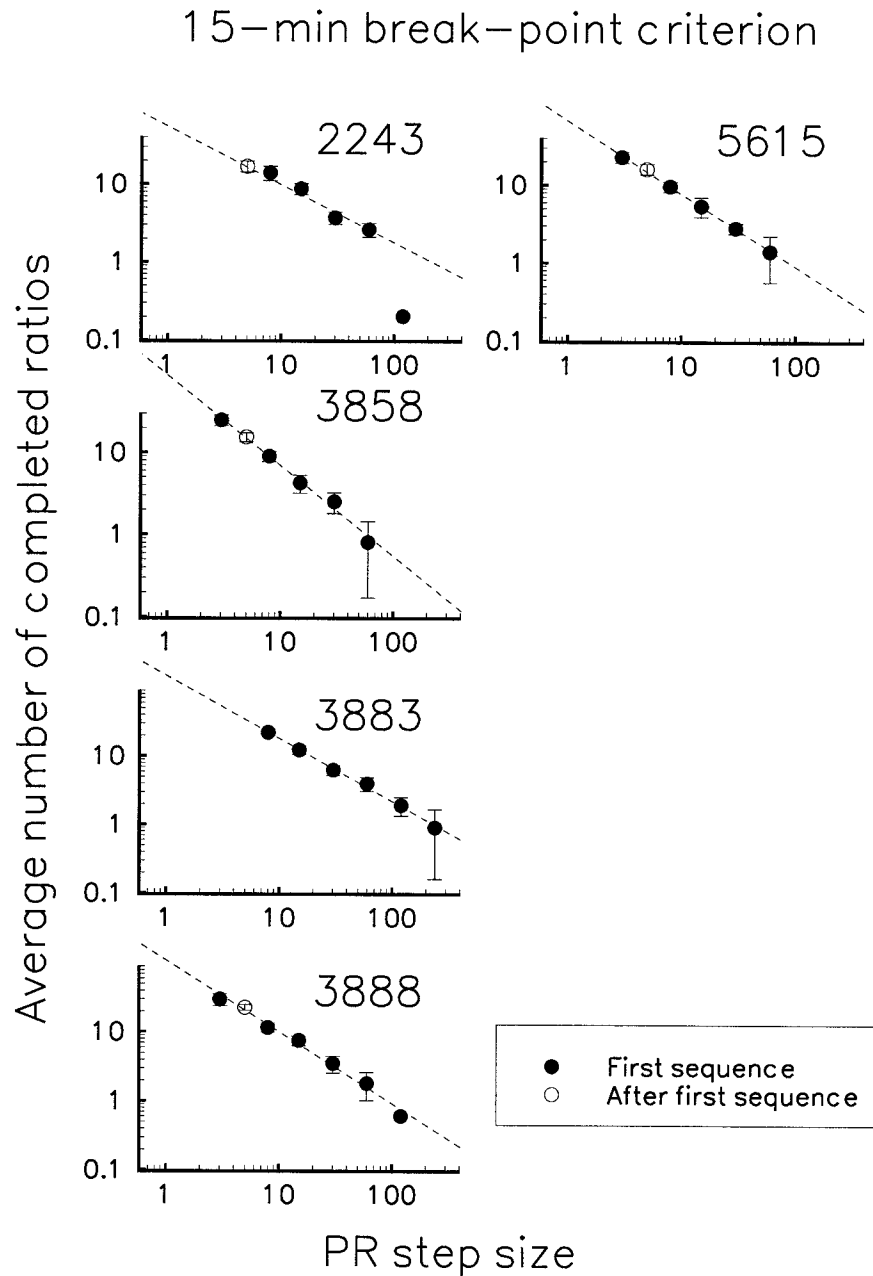


Fig. 4. Average number of completed ratios as a function of PR step size for each subject with the 15-min break-point criterion. Other plotting conventions are the same as in Figure 3.

with the 5-min criterion, the average rate of responding decreased across increasing step sizes for most subjects (not Subjects 5642 or 5775). Response rates were fairly constant over a range of step sizes for Subjects 5642 and 5775. In addition, Figure 5 highlights dif-

ferences in performances observed for some subjects across the first and second sequences of increasing step-size conditions. For example, the average response rates for Subject 5615 across the first sequence of step sizes increased slightly and then decreased; in the

Table 2

Parameter values (a and b) and proportion of variance accounted for (R^2) by the best fitting functions between average number of completed ratios and step size [$y = b(x^a)$].

Pigeon	a	b	R^2
5-min break-point criterion			
2243	-0.87	84.20	.98
3858	-1.01	51.41	.99
3883	-0.92	125.30	.99
3888	-0.87	52.66	.99
5615	-0.86	53.28	.91
5642	-0.73	62.95	.97
5775	-0.99	245.17	.98
15-min break-point criterion			
2243	-0.74	53.79	.86
3858	-1.11	89.20	1.00 ^a
3883	-0.92	150.02	1.00 ^a
3888	-1.04	110.02	.97
5615	-0.94	68.60	.99

^a These values have been rounded up (i.e., they are greater than 0.995).

second sequence, the function began at a much higher level and only decreased with increasing step sizes. Figure 6 shows that with the 15-min criterion, the average response rates declined across increasing step sizes, and the decreases were less variable than those observed with the 5-min break-point criterion. Response rates in the 15-min criterion condition were lower than those observed with the 5-min criterion for each pigeon.

Preratio Pauses

Figure 7 shows preratio-pause durations as a function of position in the PR for Subject 3858 during the 15-min criterion condition. The data shown here are representative of the typical patterns of pausing observed in every subject, and there were no major differences in patterning observed during the 5-min and 15-min criterion conditions. Pauses were defined as the time between reinforcer delivery (or, for the first ratio, the start of the session) and the first response in the following ratio; if a session was completed with no responses in the final ratio, the preratio pause was scored as equal to the break-point criterion. Data are presented from the first and last sessions of the 10-session block meeting the stability criteria in each condition, and individual panels correspond with each

step-size condition. Preratio-pause durations tended to remain relatively short across a number of progressively increasing ratio requirements, after which longer pauses abruptly occurred. For example, in the PR 3 condition (upper left panel) preratio pauses were brief for about 20 ratios, after which pause durations abruptly increased. Increases in step size resulted in fewer and fewer ratios in the initial short-pause-duration period, but the sudden increase in pause durations was typically observed at every step size. In some cases (e.g., the open circles in the PR 30 and the PR 60 panels), preratio pauses remained short across the entire session; in these cases, the pause that satisfied the break-point criterion occurred during the subject's ratio run. No consistent relations were observed between step size or break-point criterion and the frequency of sessions ending with pauses that occurred during ratio runs.

DISCUSSION

The results of this experiment replicated several aspects of PR performance that have been described in previous reports, but they differed from the existing literature in other respects. In line with the findings of numerous laboratories (e.g., Baron et al., 1992; Findley, 1958; Thomas, 1974), moment-to-moment patterns of responding on PR schedules of food delivery appeared similar to the break-and-run performance commonly observed on FR schedules (e.g., Ferster & Skinner, 1957), with bouts of rapid and sustained key pecking preceded by periods in which no pecking was observed. The duration of each period of pausing was an orderly function of both (a) the current requirements of the PR schedule (i.e., position in the progression) and (b) step-size magnitude (see Figure 7), a finding that replicates and extends previous research (e.g., Baron et al., 1992).

For the most part, the present data set indicates that step-size magnitude did not influence breaking points in a reliable manner. This was the case for 6 of 7 subjects after an extensive examination of different step sizes with the break-point criterion fixed at 5 min. When the break-point criterion was 15 min, the results were consistent across all 5 subjects. This outcome represents the most extreme departure from previously reported re-

5-min break-point criterion

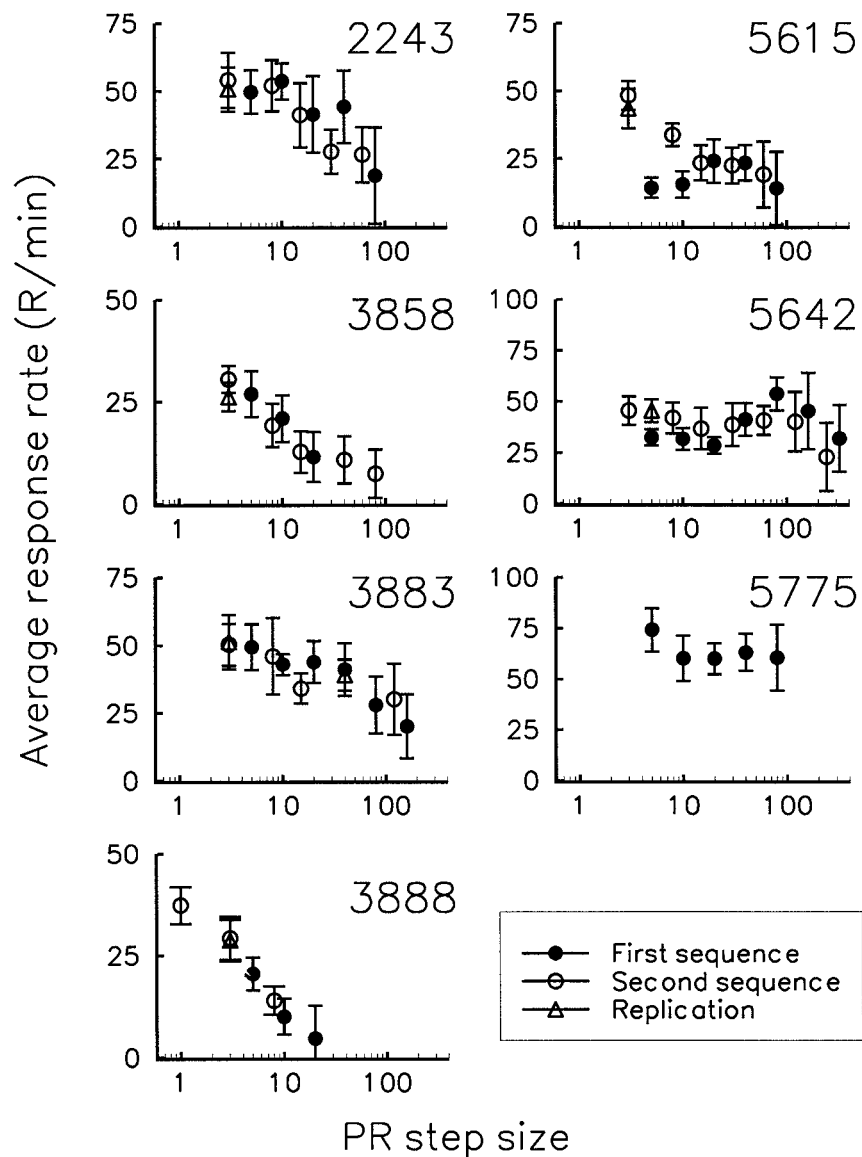


Fig. 5. Average response rates as a function of PR step size for each subject with the 5-min break-point criterion. Note that both axes are scaled logarithmically.

sults indicating that breaking points increase as a function of step-size magnitude (e.g., Hodos & Kalman, 1963). The procedures employed in the present study and by Hodos and Kalman, it may be noted, differed in numerous ways, including the species of subject studied, the response required, the reinforcer-

ment and drug-administration histories of the subjects, the reinforcer used, and the length of exposure to each step-size condition, among other variables.

The length of exposure to each step-size condition, in particular, may have played a significant role in determining the form of

15-min break-point criterion

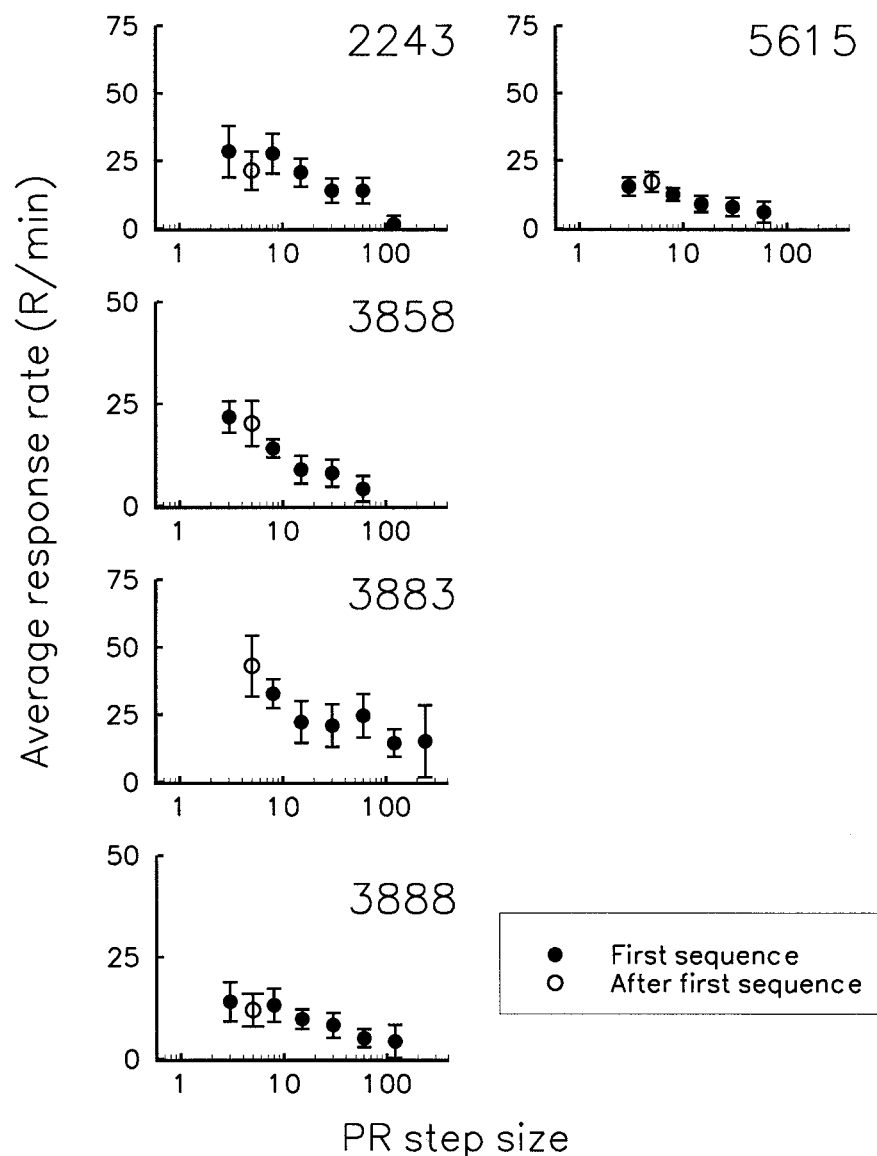


Fig. 6. Average response rates as a function of PR step size for each subject with the 15-min break-point criterion. Plotting conventions are the same as in Figure 5.

the relation between step-size magnitude and average breaking point. In this experiment, each step-size condition remained in effect until performance stabilized (range, 25 to 94 sessions). In contrast, Hodos and Kalman's (1963) procedure arranged for only six sessions of exposure to a particular step size. In

the present experiment, stable breaking points (i.e., the last 10 sessions in a condition) did not differ markedly across step-size conditions within individual subjects, but short-term alterations in breaking points were commonly observed in transitions between step-size conditions. We could have plotted

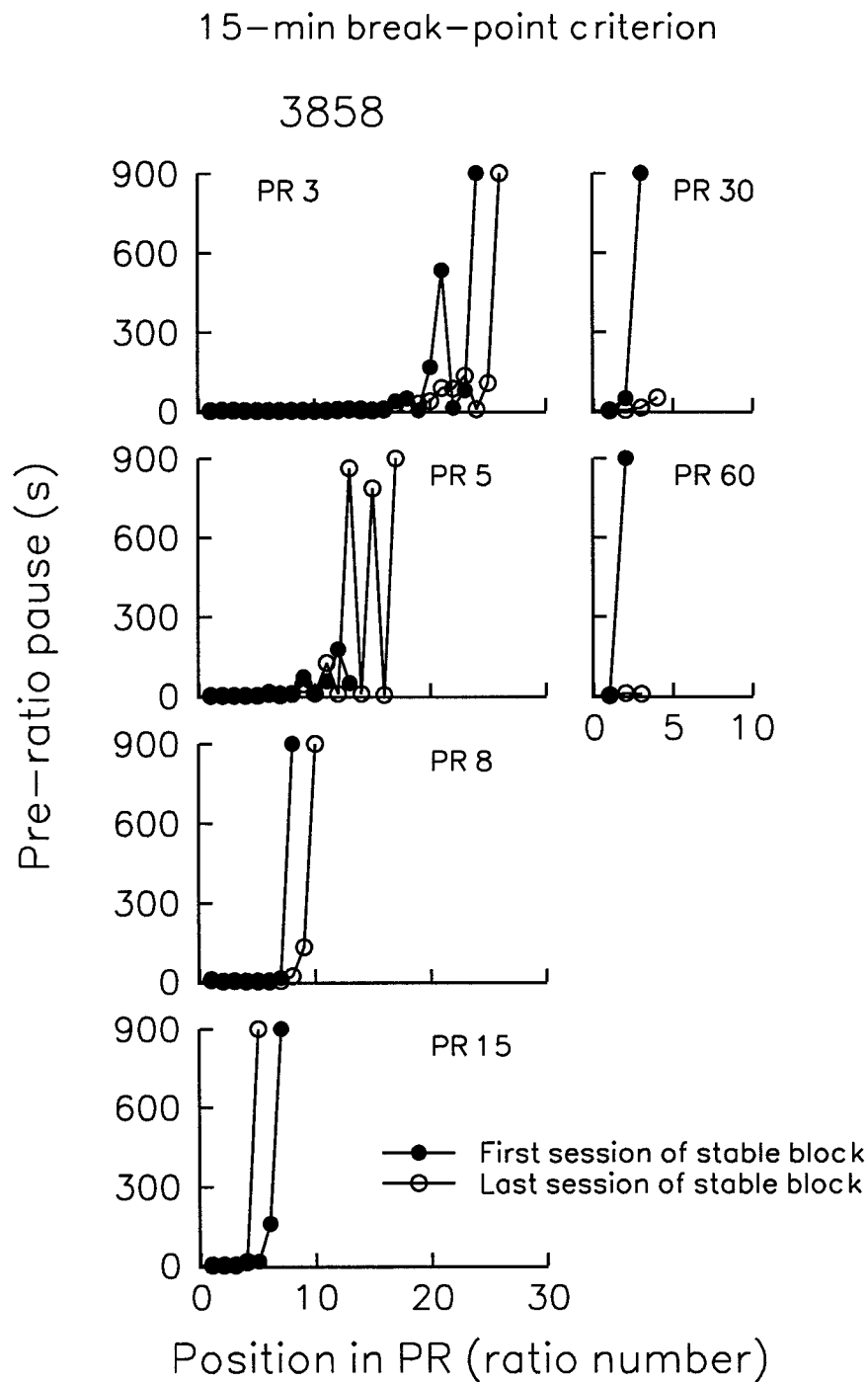


Fig. 7. Preratio pauses as a function of position in the PR for Subject 5642 with the 5-min break-point criterion. Filled circles correspond with the first session and open circles with the last session of the 10-session block that met the stability criteria for each step-size condition.

break-point data from the first six sessions of each condition in our study, but those data could not have been considered representative of stable performance in these circumstances; in fact, those data were rather variable.

The present study showed that the average number of completed ratios and the average response rates per session decreased with increasing step sizes. These findings partially answer calls made for a broader description of behavior maintained by PR schedules (e.g., Katz, 1990; Stewart, 1975). The effects of varying both step size and break-point criteria were quantified extremely well with reference to the average number of ratios completed per session. A similar focus on the number of completed ratios per session has been supported by investigators studying drug self-administration. This measure is more amenable to analysis with inferential statistics because it does not violate the assumption of variance homogeneity (e.g., Depoortere et al., 1993; Loh & Roberts, 1990). In this experiment, a power function with two free parameters [i.e., $y = b(x^a)$] provided an excellent fit to the relation between step size and the average number of completed ratios per session for every subject.

Not only did the functions relating average number of completed ratios to step size decrease in an orderly fashion for all subjects, but the values of the free parameters defining the best fitting functions were fairly similar across subjects. The values of the parameter a , representing the slope of each function in log-log coordinates, were generally clustered around -1 , and changing the break-point criterion from 5 to 15 min did not significantly alter these values. In terms of PR performance, if a were exactly equal to -1 , breaking points would be totally insensitive to changes in the step size. The parameter b , on the other hand, varied more widely across subjects (range, 51.41 to 245.17), but was shown to be sensitive to changes in the break-point criterion. Values of b can be interpreted as the average number of ratios expected to be completed at a step size of one; the average number of ratios expected to be completed at any other step size is equal to $b/\text{step size}$ (this interpretation of b is true only if a is equal to -1).

If the predictable and quantifiable relation

between step size and average number of completed ratios observed in the present experiment could be replicated in other laboratories, the relation itself might serve as a useful tool. That is, research programs designed to assess the effects of other variables (e.g., drug administration, reinforcer magnitude, brain lesions, etc.) on PR performance might first demonstrate this functional relation as a baseline condition and then apply other variables across several step-size conditions. The values of a and b observed during treatment conditions, relative to the values observed during baseline, could be considered indices of the treatment's effect.

To test this idea, the average number of ratios completed per session across different step-size conditions was estimated from figures presented in Hodos and Kalman (1963) and Thomas (1974) and are replotted here in Figure 8. Although Thomas' experiment was not specifically designed to assess the effects of increment size on PR performance, each subject was exposed to three different step-size conditions. Summarizing data from both studies, the average number of ratios completed declined across increasing step sizes. Although only a few step-size conditions were studied in both of these experiments, the general pattern of data points is consistent with that observed in the present study: The decline in average number of completed ratios is fairly linear in log-log coordinates. Power functions described these data well; the best fitting functions produced R^2 values of .95 or above for every subject (range, .95 to .99). Values of the parameter a for each subject in Thomas' experiment were similar to those observed in the present study, and ranged from $-.84$ to $-.93$. In Hodos and Kalman's (1963) study, however, the values of a were significantly smaller for both subjects in both conditions (during food deprivation, the values were $-.60$ and $-.65$; in free-feeding conditions, the values were $-.54$ and $-.71$). The parameter b ranged from 68.92 to 178.62 in Thomas' study and from 45.15 to 97.06 in Hodos and Kalman's. All but one of these b values (not 45.15) fell within the range of those reported here.

Hodos and Kalman's (1963) data also provide a precedent in which the functional relation between the average number of ratios completed and step size was shown to be sen-

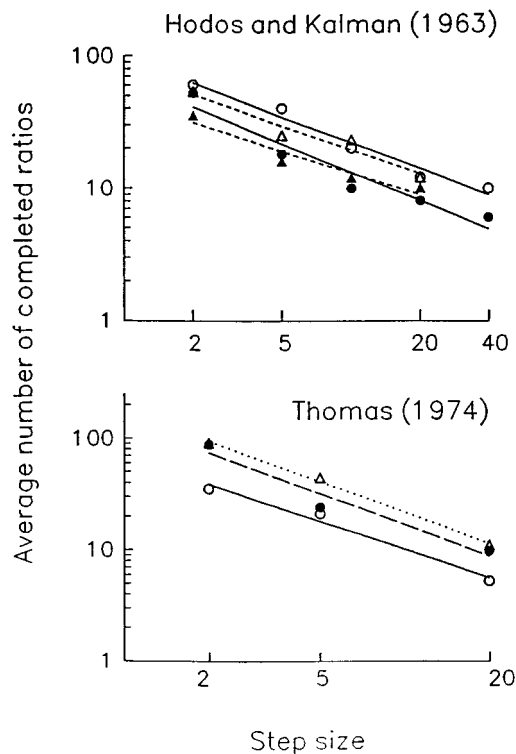


Fig. 8. Average number of completed ratios per session as a function of PR step size for subjects in Hodos and Kalman's (1963) and Thomas' (1974) experiments (data were estimated from each report's Figure 2). The straight lines show the best fitting functions for each subject's data. In the upper panel, open symbols correspond with data collected during restricted-food-intake conditions (80% free-feeding body weight), and filled symbols correspond with data collected during free-feeding conditions (the reinforcer in this study was sweetened condensed milk). Dashed lines show data from 1 subject, and solid lines show data from the other subject. In the lower panel, individual-subject data are represented by the different symbols and line types. Note that both axes are scaled logarithmically in both panels.

sitive to the application of an experimental treatment (i.e., the function served as a baseline). Figure 8 shows that restricting subjects' food intake resulted in upward shifts of the function for each rat, relative to those observed during free-feeding conditions. The values of b increased from 66.49 to 97.06 for 1 subject and from 45.15 to 77.03 for the other, reflecting this upward shift, whereas a values remained relatively stable (a increased for 1 subject and decreased for the other, but both changes were slight: from $-.54$ to $-.60$ in one and from $-.71$ to $-.65$ in the other). Hence, the speculations offered above, con-

cerning the use of this inverse relation between the average number of ratios completed per session and step size as a baseline against which the effects of other variables (e.g., drug administration, lesions of the brain, etc.) might be assessed, cannot be considered too farfetched, because such a demonstration can be found in the existing literature. In brief, Hodos and Kalman's study showed that an experimental treatment can affect a and b differently. Whether certain clusters of experimental treatments generally affect only one or the other of the two parameters remains a topic for future research.

Data from this experiment suggest that breaking points are relatively unaffected by changes in step size, but they can be altered by changes in break-point criterion. This outcome is particularly relevant to the growing use of PR schedules in drug self-administration studies, in which procedural variations across laboratories are the rule rather than the exception. Insofar as breaking points are thought to measure a drug reinforcer's strength (cf. Hodos, 1961), it seems wise to experimentally determine which procedural variables are able to influence this estimate. In our view, no reinforcer is likely to maintain a fixed breaking point; rather, contextual variables (such as current degree of deprivation for the reinforcer of interest, degree of deprivation for other reinforcers typically earned by the subject, the presence or absence of alternative reinforcers, the schedules by which the alternatives may be earned, the introduction or removal of conditioned or discriminative stimuli, etc.) certainly play a significant role in determining break-point magnitude. These issues are without exception empirical, but experiments designed to explore the contributions of procedural factors to variations in breaking points observed on PR schedules of drug delivery are rare (but see Rowlett, Massey, Kleven, & Woolverton, 1996).

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